BUDKER-INP 2003-7

MEASUREMENT OF $\gamma\gamma$ and γe LUMINOSITIES AT PHOTON COLLIDERS *

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Abstract

Methods of $\gamma\gamma$, γe luminosities measurement at photon colliders based on Compton scattering of laser photons on high energy electrons at linear colliders are considered.

1 Introduction

In addition to e^+e^- physics, linear colliders provide a unique opportunity to study $\gamma\gamma$ and γe interactions at high energies and luminosities [1, 2]. High energy photons can be obtained using Compton backscattering of laser light off high energy electrons. This option is included in Technical Design of the linear collider TESLA [4] and is considered for all other project of linear colliders [5, 6, 7].

Spectrum of photons after Compton scattering is broad with characteristic peak at maximum energies. Photons can have circular or linear polarizations depending on their energies and polarizations of initial electrons and laser photons. Due to angle-energy correlation, in Compton scattering the $\gamma\gamma$ luminosity can not be described by convolution of some photon spectra. Due to complexity of processes in the conversion and interaction regions an accuracy of prediction by simulation will be rather poor, therefore one should measure all luminosity properties experimentally.

Below we consider some general features of $\gamma\gamma$, γe processes, give example of luminosity spectra and then consider methods for measurement of $\gamma\gamma$, γe luminosities.

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*Talk at the Intern. Workshop on Physics and Detectors at Linear Collider, LCWS2002, August 26-30, 2002, Jeju Island, Korea.

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2 General features of luminosities and cross sections

In general case the number of events in $\gamma\gamma$ collision is given by [2]

$$d\dot{N}_{\gamma\gamma\,\to X} = dL_{\gamma\gamma}\sum_{i,j=0}^{3}\langle\xi_i\tilde{\xi_j}\rangle\sigma_{ij}, \tag{1}$$

where ξ_i are Stokes parameters, $\xi_2 \equiv \lambda_\gamma$ is the circular polarization, $\sqrt{\xi_1^2+\xi_3^2} \equiv l_\gamma$ the linear polarization and $\xi_0 \equiv 1$. Since photons have wide spectra and various polarizations, in general case one has to measure 16 two dimensional luminosity distributions $d^2L_{ij}/d\omega_1 d\omega_2$, $dL_{ij} = dL_{\gamma\gamma}\langle\xi_i\tilde{\xi_j}\rangle$, where the tilde sign marks the second colliding beam.

Among 16 cross sections σ_{ij} there are three most important which do not vanish after averaging over spin states of final particles and azimuthal angles, that are [2]

$$\sigma^{np} \equiv \sigma_{00} = \frac{1}{2}(\sigma_\parallel + \sigma_\perp) = \frac{1}{2}(\sigma_0+\sigma_2)$$
$$\tau^c \equiv \sigma_{22} = \frac{1}{2}(\sigma_0-\sigma_2) \quad \tau^l \equiv \frac{1}{2}(\sigma_{33}-\sigma_{11}) = \frac{1}{2}(\sigma_\parallel - \sigma_\perp) \tag{2}$$

Here $\sigma_\parallel, \sigma_\perp$ are cross sections for collisions of linearly polarized photons with parallel and orthoganal relative polarizations and σ_0 and σ_2 are cross sections for collisions of photons with J_z of two photons equal 0 and 2, respectively.

If only these three cross sections are of interest than (1) can be written as

$$d\dot{N}_{\gamma\gamma\,\to X} = dL_{\gamma\gamma}\,(d\sigma^{np} + \langle\xi_2\tilde{\xi_2}\rangle d\tau^c + \langle\xi_3\tilde{\xi_3} - \xi_1\tilde{\xi_1}\rangle d\tau^l)\,. \tag{3}$$

Substituting $\xi_2 \equiv \lambda_\gamma$, $\tilde{\xi_2} \equiv \tilde{\lambda}_\gamma$, $\xi_1 \equiv l_\gamma \sin 2\gamma$, $\tilde{\xi_1} \equiv -\tilde{l}_\gamma \sin 2\tilde{\gamma}$, $\xi_3 \equiv l_\gamma\cos 2\gamma$, $\tilde{\xi_3} \equiv \tilde{l}_\gamma \cos 2\tilde{\gamma}$ and $\Delta\phi = \gamma - \tilde{\gamma}$ (azimuthal angles for linear polarizations are defined relative to one x axis), we get

$$\begin{aligned}
d\dot{N} &= dL_{\gamma\gamma}(d\sigma^{np} + \lambda_\gamma\tilde{\lambda}_\gamma\, d\tau^c + l_\gamma\tilde{l}_\gamma\cos 2\Delta\phi\, d\tau^l)\\
&\equiv dL_{\gamma\gamma}\, d\sigma^{np} + (dL_0 - dL_2)d\tau^c + (dL_\parallel - dL_\perp)\, d\tau^l\\
&\equiv dL_0 d\sigma_0 + dL_2 d\sigma_2 + (dL_\parallel - dL_\perp)\, d\tau^l\\
&\equiv dL_\parallel\, d\sigma_\parallel + dL_\perp\, d\sigma_\perp + (dL_0 - dL_2)\, d\tau^c\,,
\end{aligned} \tag{4}$$

where $dL_0 = dL_\gamma(1+\lambda_\gamma\tilde{\lambda}_\gamma)/2$, $dL_2 = dL_\gamma(1-\lambda_\gamma\tilde{\lambda}_\gamma)/2$, $dL_\parallel = dL_\gamma(1+l_\gamma\tilde{l}_\gamma\cos 2\Delta\phi)/2$, $dL_\perp = dL_\gamma(1-l_\gamma\tilde{l}_\gamma\cos 2\Delta\phi)/2$.

So, one should measure (not only in a general case) $dL_{\gamma\gamma}$, $\langle\lambda_\gamma\tilde{\lambda}_\gamma\rangle$, $\langle l_\gamma\tilde{l}_\gamma\rangle$ or alternatively $dL_0, dL_2, dL_\parallel, dL_\perp$. If both photon beams have no linear polarization

or no circular polarization, the luminosity can be decomposed in two parts: L_0 and L_2, or $L_\parallel$ and $L_\perp$, respectively.

For example, for scalar resonances such as the Higgs boson, $\sigma_2 = 0$, while $\sigma_\parallel = \sigma_0$, $\sigma_\perp = 0$ for $CP = 1$ and $\sigma_\perp = \sigma_0$, $\sigma_\parallel = 0$ for $CP = -1$, then

$$d\dot{N} = dL_{\gamma\gamma}\, d\sigma^{np}(1 + \lambda_\gamma\tilde{\lambda}_\gamma \pm l_\gamma\tilde{l}_\gamma \cos 2\Delta\phi)\,. \tag{5}$$

In γe collisions general formulae are similar to (1) but Stokes parameters for the second particle are replaced by the electron spin vector $\boldsymbol{\zeta}$ (the double mean electron helicity $2\lambda_e = \zeta_3$). Besides $dL_{\gamma\mathrm{e}}$ the most important characteristic is $\langle\lambda_e\lambda_\gamma\rangle$ (as function of E_e and E_γ), but in some cases λ_e and λ_γ should be known separately, in the process $\gamma\mathrm{e} \to W\nu$, for instance.

Expected $\gamma\gamma$, γe luminosity spectra at TESLA(500) are presented in Fig.1 [8, 4, 9]. The luminosities in the high energy peaks are about $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ both for $\gamma\gamma$ and γe collisions [4].

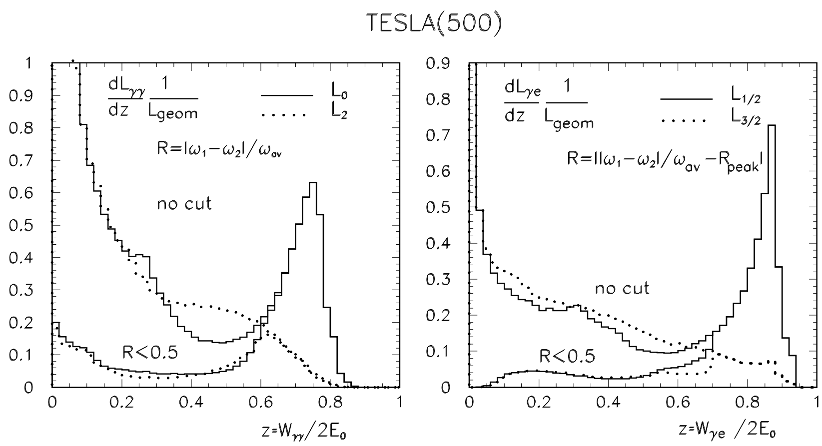

Figure 1: Left: $\gamma\gamma$ luminosity spectra; right: γe luminosity spectra at TESLA. Solid lines for J_z of two colliding photons equal to 0, dotted lines for $J_z = 2$ (1/2 and 3/2 in case of γe collisions).

3 Measurement of $\gamma\gamma$ luminosities

The best process for the measurement of the $\gamma\gamma$ luminosity is $\gamma\gamma \to l^+l^-$ $(l = \mathrm{e}, \mu)$ [2, 10, 11, 4]. Another QED process with large cross section is $\gamma\gamma \to l^+l^-l^+l^-$ [1, 13]. The process $\gamma\gamma \to W^+W^-$ was also suggested for the luminosity measurement [12], but at first its cross section has to be measured as it may differ from prediction of the Standard Model and presents special physics interest by itself.

$\underline{\gamma\gamma \to l^+l^-}$. The cross section in c.m.s. at not too small angles (see [4])

$$d\sigma = \frac{2\pi\alpha^2}{{W_{\gamma\gamma}}^2}\left[(1-\lambda_\gamma\tilde{\lambda}_\gamma)\frac{(1+\cos^2\theta)}{(1-\cos^2\theta)} - l_\gamma\,\tilde{l}_\gamma\cos\left(4\varphi - 2(\gamma+\tilde{\gamma})\right)\right]\frac{d\varphi}{2\pi}d(\cos\theta)\,, \quad (6)$$

where $\lambda_\gamma, \tilde{\lambda}_\gamma$ the circular polarizations, $l_\gamma, \tilde{l}_\gamma$ linear polarizations of photons, $\gamma, \tilde{\gamma}$ azimuthal angles of photon linear polarizations, φ the azimuthal angle of the lepton plane. One can see that the cross section is zero for $\lambda_\gamma = \tilde{\lambda}_\gamma = \pm 1$ (or $J_z = 0$). Thus, lepton pairs are produced only in collisions of photons with total $J_z = 2$. The suppression factor for $J_z = 0$ is $m_l^2/W_{\gamma\gamma}^2$ [4]. This process can measure only L_2, for measurement of L_0 one can change the polarization of one beam to opposite for part of the time [10, 11]. The product of linear polarizations $\langle l_\gamma \tilde{l}_\gamma\rangle$ can be measured by azimuthal variation of the cross section at the large angles θ. The total cross section

$$\sigma_2(|\cos\theta| < a) \approx \frac{4\pi\alpha^2}{W_{\gamma\gamma}^2}\left[2\ln\left(\frac{1+a}{1-a}\right) - 2a\right]. \quad (7)$$

For example, $\sigma(|\cos\theta| < 0.9) \approx 10^{-36}/W_{\gamma\gamma}^2[\text{TeV}]\ \text{cm}^2$, and at TESLA(500) for 10^7 sec one can expect about 10^6 of $\mathrm{e}^+\mathrm{e}^-$ and $\mu^+\mu^-$ events in the high energy peak.

The invariant mass spectrum of $\mu^+\mu^-$ pairs in the detector is shown in Fig.2. For

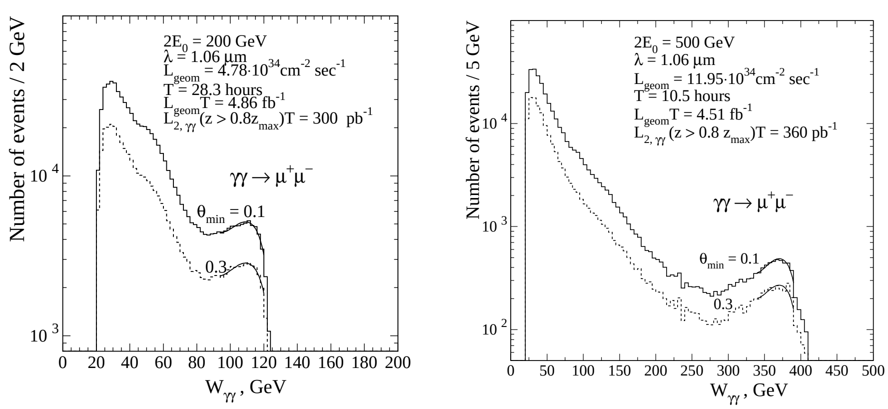

Figure 2: Distribution of pairs on the invariant mass in the process $\gamma\gamma \to \mu^+\mu^-$; left: $2E_0 = 200$ GeV, right: $2E_0 = 500$ GeV.

the minimum detection angle $\theta = 0.3$ rad and 10^7 sec run the expected statistical accuracy of the peak value of $dL/dW_{\gamma\gamma}$ is about 0.07 % and 0.14 % for $2E_0 = 200$ and 500 GeV, respectively. This is much better than necessary for the Higgs study where the accuracy for branchings not better than 1% is expected.

<u>$\gamma\gamma \rightarrow l^+l^-\gamma$</u>. This process is of interest because the photon emission removes the suppression of the lepton production in the case of $J_z = 0$. The cross section for this process as a function of the minimum photon energy obtained by the ComHEP code [14] is presented in Fig.3. Indeed, the cross section for this case is not negligible, but lower than for $J_z = 2$ without photons by a factor of 300.

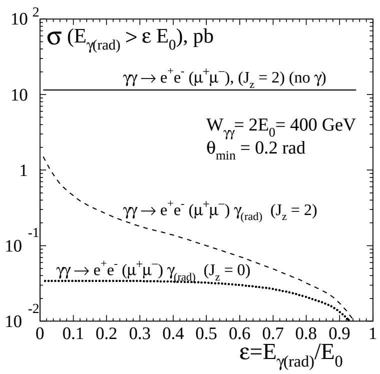

Figure 3: The cross section of the process $\gamma\gamma \rightarrow l^+l^-\gamma$ vs the minimum energy of the emitted photons.

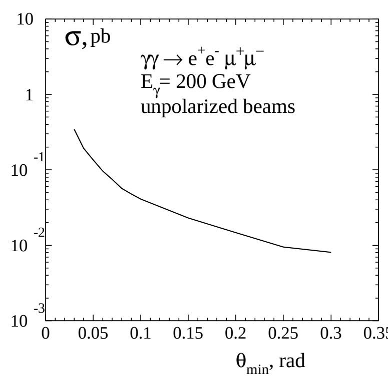

Figure 4: The cross section of the process $\gamma\gamma \rightarrow e^+e^-\mu^+\mu^-$ vs the minimum polar angle of all final particles.

<u>$\gamma\gamma \rightarrow l^+l^-l^+l^-(l = e, \mu)$</u>. This process is of interest [1, 13] because it has large total cross section and weakly depends on photon polarizations, therefore it could be used together with $\gamma\gamma \rightarrow l^+l^-$ for measurement of L_0 and L_2 simultaneously. Unfortunately, at large angles, where particle momenta can be measured with a high accuracy, the cross section is rather small. The cross section obtained by ComHEP for the process $\gamma\gamma \rightarrow e^+e^-\mu^+\mu^-$ at the photon energies 2×200 GeV is shown in Fig. 4. At small angles main contribution gives the peripheral diagram and the cross section depends on the minimum angle as $1/\theta^2$. At the angles above 0.1 rad main contribution give diagrams where the second pair is emitted by one of leptons of the first pair, here one can expect the logarithmical dependence on the angle as for the one pair production. In the region $\theta > 0.2$ rad covered by the tracking system it is 1000 times smaller than the cross section for one pair. In principle, one can install a fine segmented calorimeter at the angles down to 20 mrad, where backgrounds are acceptable, and detect the process $\mathrm{e^+e^-e^+e^-}$ with the cross section about 1 pb at $2E_0 = 500$ GeV with a rather good energy resolution. Nevertheless, it can not compete with the process of one pair lepton production which has more than one order higher counting rate, better resolution on invariant masses and much lower systematics.

4 Measurement of γe luminosity

Here two QED processes are of interest: $\gamma e \to \gamma e$ and $\gamma e \to e^- e^+ e^-$. The cross section for the first process is proportional to $\alpha^2/W_{\gamma e}^2$, the second one is of the higher order on α: $\alpha^3/(W_{\gamma e}\theta)^2$, however at small angles its cross section is even larger.

$\gamma e \to \gamma e$. Cross section in c.m.s. at $\theta \gg 1/\gamma$

$$d\sigma = \frac{\pi\alpha^2}{2{W_{\gamma e}}^2}\left[(1-2\lambda_e\lambda_\gamma)(1-\cos\theta_\gamma) + (1+2\lambda_e\lambda_\gamma)\frac{4}{1-\cos\theta_\gamma}\right]d(\cos\theta_\gamma), \qquad (8)$$

where λ_γ and λ_e ($|\lambda_e| < 1$) are the photon and electron helicities, z-axis is along the initial direction of the electron. The first term corresponds to the case when helicities of the electron and photon have opposite signs, i.e. $|J_z| = 3/2$, the second, dominant term, to $|J_z| = 1/2$. The cross section for unpolarized beams is shown in Fig. 5.

Additional problem in γe collisions is connected with the fact that the photon can come from two directions (if both electron beams collide with laser photons). Luminosities for each direction should be measured independently. According to (8), the cross section with $|J_z| = 3/2$ and $|J_z| = 1/2$ are comparable at $\theta_\gamma \sim \pi$ and, it seems, that one can measure both luminosities $L_{1/2}$ and $L_{3/2}$ fitting the angular distributions. However, due to two possible photon directions the effective cross section is $\sigma = (\sigma(\theta) + \sigma(\pi - \theta))/2$, and $\sigma_{1/2}$ dominates at all angles. We have checked the statistical accuracy of measurement of $L_{1/2}$ and $L_{3/2}$. Let the number of produced events in these polarization states be $N_{1/2}$ and $N_{3/2}$. In the ideal case $\sigma_{Li}/L_i = 1/\sqrt{N_i}$, in reality the accuracies depend on the ratio of luminosities as shown in Fig. 6. One can see that $L_{3/2}$ can be measured with an accuracy close to $1/\sqrt{N_i}$ only when $L_{1/2} \ll L_{3/2}$. For the measurement of both $L_{1/2}$ and $L_{3/2}$ with a high accuracy one should invert polarization of one beam to opposite in the same way as for $\gamma\gamma$ collisions. For γe luminosity spectra at TESLA(500) (see Fig.1) and beams with equal polarizations the number of events in the high energy peak for 10^7 sec is $N_{1/2} = 3 \times 10^5$ and $N_{3/2} = 5 \times 10^3$. The luminosities $L_{1/2}$ and $L_{3/2}$ are measured with accuracies 0.3% and 20%, respectively. After inversion of polarization for one beam, distributions for $L_{1/2}$ and $L_{3/2}$ replace each other and new number of events are $N_{1/2} = 5 \times 10^4$, $N_{3/2} = 3 \times 10^4$ and the accuracies for $L_{1/2}$ and $L_{3/2}$ are 0.8% and 1.8%, respectively. Thus, the measurement with inverted polarization improves the accuracy for $L_{3/2}$ (that was before the inversion) from 20 % to 0.8%.

$\gamma e \to e^- e^+ e^-$. The cross section of the Bethe-Heitler process for the case when all three final particles have angles above $\theta_{\min}$ is shown in Fig. 5. As was mentioned

before, at $\theta < 70$ mrad it is larger than that for γe $\to$ γe. It is not small even in the region above 0.15–0.2 rad where detectors measure precisely parameters of all particles. The cross section of this process only weakly depends on the polarization of initial particles. Tohether with the process γe $\to$ γe it allows to measure $L_{3/2}$ with sufficiently good accuracy without the inversion of beam polarizations or can be used for the cross check.

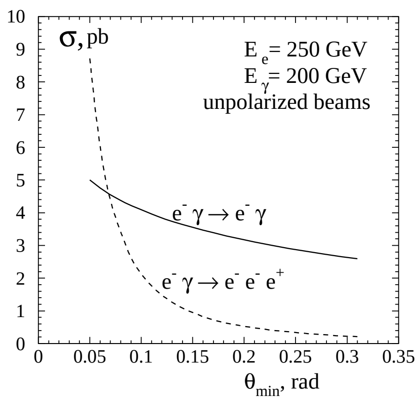

Figure 5: The cross section of processes for γe luminosity measurement as a function of the minimum detection angle.

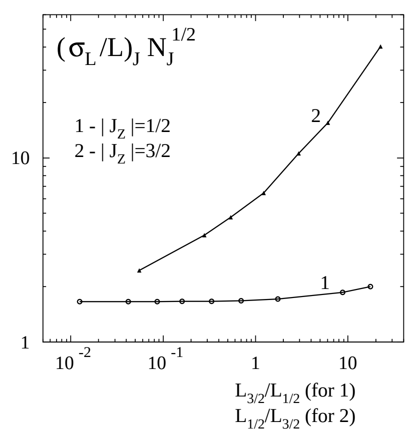

Figure 6: Statistical accuracy of $L_{1/2}$ and $L_{3/2}$ as a function of the luminosities ratio.

$\gamma e \to eZ$. For study of some processes, such as γe $\to$ $W\nu$, the independent measurement of λ_e and λ_γ is necessary. In the Compton process at $\theta \gg 1/\gamma$ the terms containing such dependence are neglegibly small (see [4]). For the measurement one can use the process γe $\to$ eZ (may be there is better one?). Its cross section for $W_{\gamma e} \gg M_Z$ and $W_{\gamma e} \sim M_Z$, respectively, is [15]

$$\sigma \propto \frac{(1+2\lambda_e\lambda_\gamma) - 0.2(2\lambda_e+\lambda_\gamma)}{1-\cos\theta_Z} + \frac{(1-2\lambda_e\lambda_\gamma) - 0.2(2\lambda_e-\lambda_\gamma)}{4}(1-\cos\theta_Z)$$

$$\sigma \propto \frac{(1-2\lambda_e\lambda_\gamma) - 0.2(2\lambda_e-\lambda_\gamma)}{1-\cos\theta_Z}. \tag{9}$$

One can see that it is possible to extract the electron and photon polarization separately assuming that their product is measured by γe $\to$ γe with a high accuracy.

5 Discussion, conclusion

The $\gamma\gamma$ luminosity for circular and linear polarized beams can be measured using the process $\gamma\gamma \to l^+l^-$. Since this cross section is negligible for $J_z = 0$, to measure of L_0 one has to invert the polarization of one beam for part of the time. The processes $\gamma\gamma \to l^+l^-\gamma$ is sensitive to $J_z = 0$ but has too small cross section. The process $\gamma\gamma \to l^+l^-l^+l^-$ has too small cross section in the large angle part of the detector with good measurement of particle momenta. Detection of this process in the region of small angles (above 20 mrad) may be useful.

In γe collisions the luminosity and product $\lambda_e\lambda_\gamma$ can be measured with a high accuracy by means of the process γe $\to$ γe. In order to measure both helicity combinations, inversion of the polarization for one of beams is necessary. The Bethe-Heitler process γe $\to$ e$^-$e$^+$e$^-$has also sufficiently large cross section, it can provide independent check of the first method and allows to improve the accuracy of $L_{3/2}$ without inversion of beam polarizations.

This work was supported in part by INTAS (00-00679) and RFBR (02-02-17884).

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